

Silicon QuBIT Workshop
Berkeley August 24th, 2009

Silicon single electron devices for quantum information processing

Marc SANQUER,
Coordinator of the AFSiD european project
and
CEA-Grenoble

Work done by Xavier JEHL, Max HOFHEINZ*, Mathieu PIERRE , Marc SANQUER, Maud VINET and Romain WACQUEZ @ CEA-DSM-INAC + CEA-LETI-MINATEC in collaboration with the AFSiD partners.

*now at UCSB

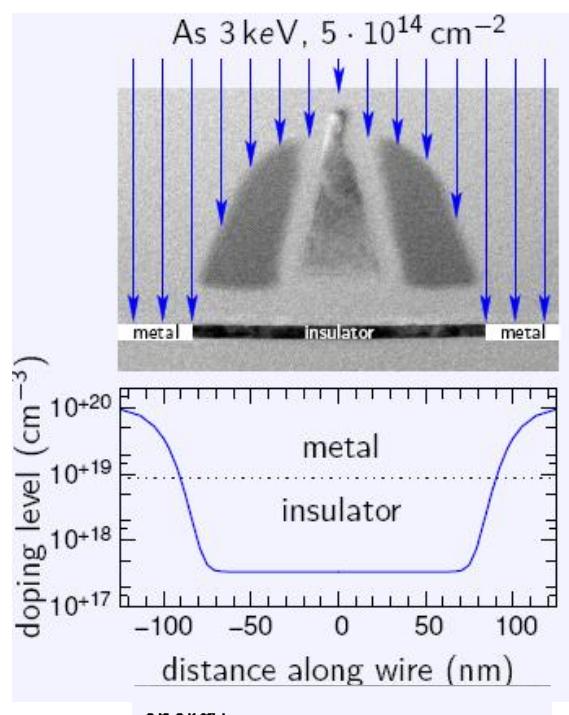


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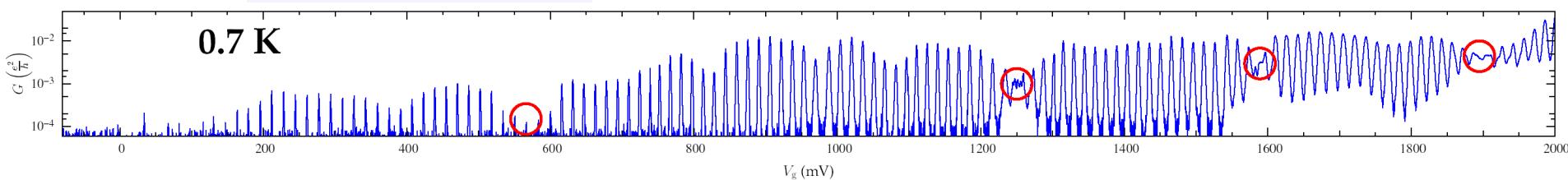
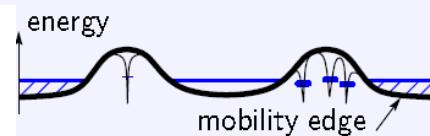
- The MOS-SET
- AFSiD project : down scaling the MOS-SET
- AFSiD project : Coupled MOS-SETs, MOS-SET with an antenna
- Single donor ionization detected with a MOS-SET
- Summary



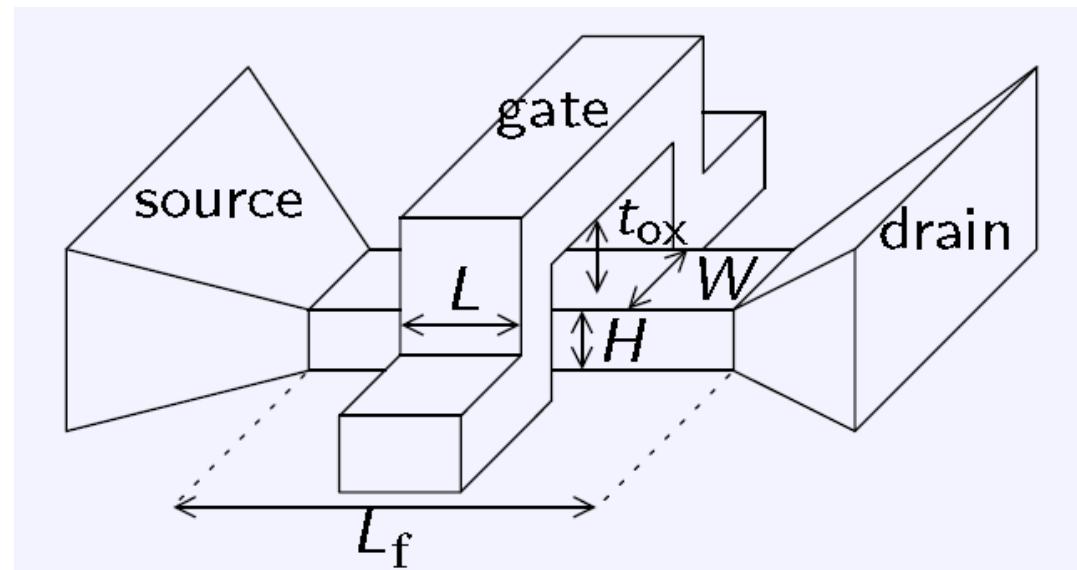
The MOS-SET: a nanowire SOI field effect transistor with underlapped source-drain junctions



@ $V_g >> 0$:



M. Hofheinz et al., APL 89 143504 (2006) and
Eur. Phys. J. B 54 299 (2006).

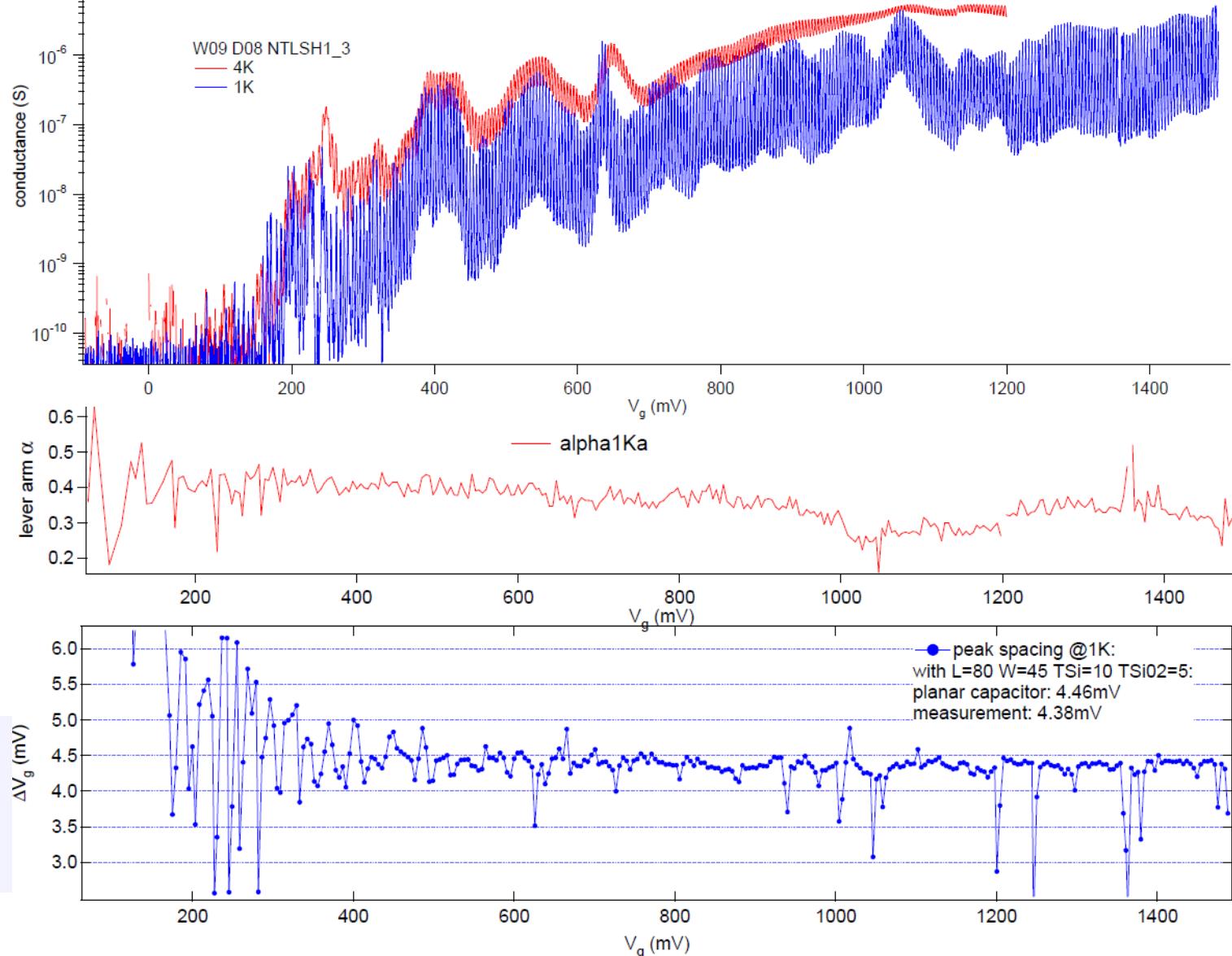
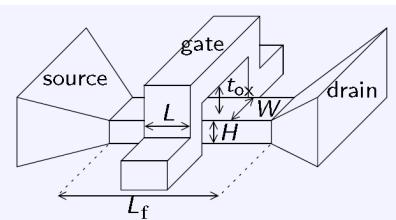


MOS-SET
Diameter 30 nm

Charging
energy=few meV

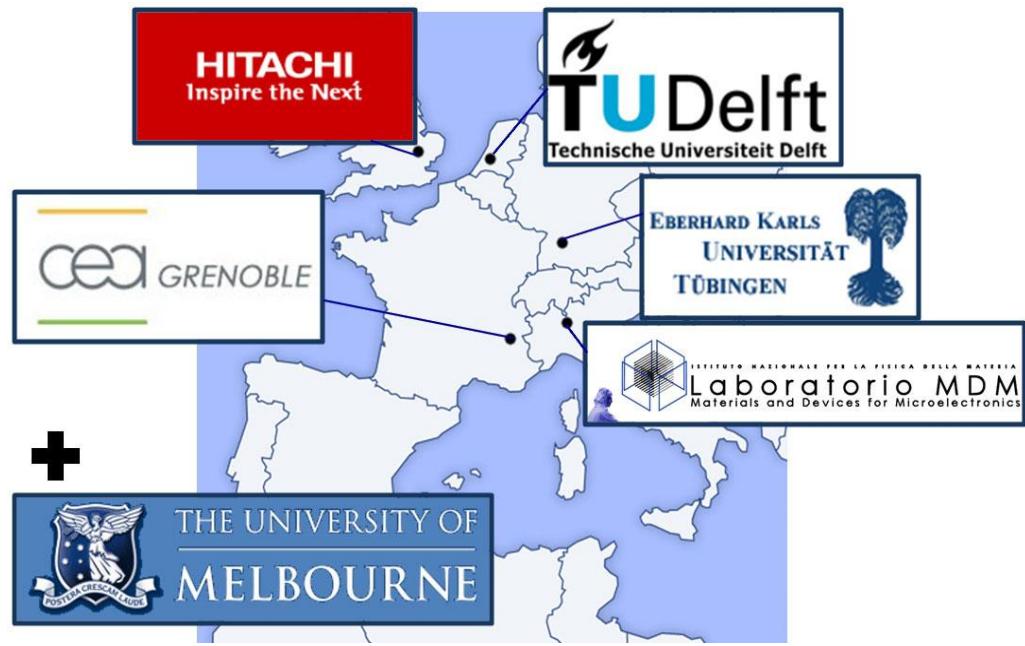
Gate capacitance=
gate-channel
overlap (3000nm^2)
capacitance

Accumulation QD:
Density of carriers
up to few 10^{13}cm^{-2}
→ up to 300
electrons without
changing the size



Atomic Functionalities on Silicon Devices

FET Proactive 2008
NanoICT
New Functionalities



Coordinator: Dr. Marc SANQUER (CEA-Grenoble)

Team Leaders: Dr. Marco FANCIULLI (Agrate-Brianza),
Pf. David JAMIESON (Melbourne), Pf. Dieter KERN (Tübingen),
Dr. Sven ROGGE (Delft), Dr. David WILLIAMS (Cambridge)



<http://www.afsid.eu>

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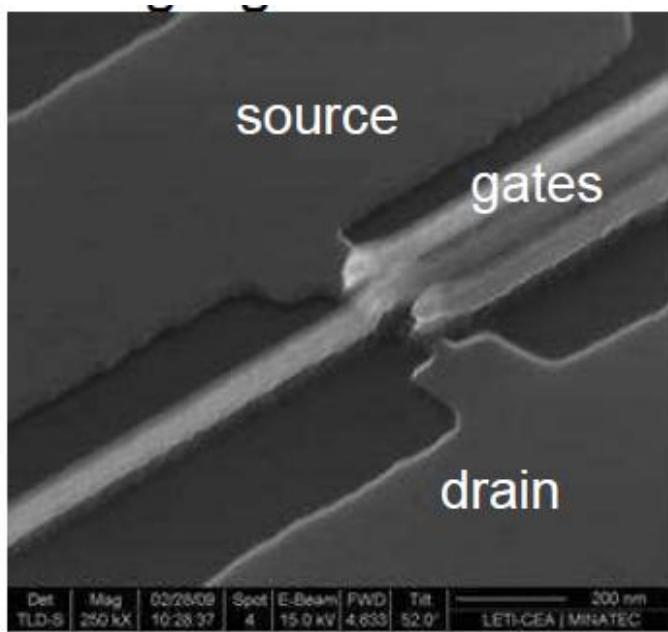
Berkeley, Au. 24th 2009

AFSiD:

- downscaling of a single MOS-SET down to gate-channel overlap of 300 nm^2
i.e. few 10' of electrons (artificial silicon atom)
Also more suitable to see the first electron in the MOS-SET.
- Coupled MOS-SET: pitch about 70 nm
- MOS-SET with antenna
- and many others devices



Coupled MOS-SETs: Very compact

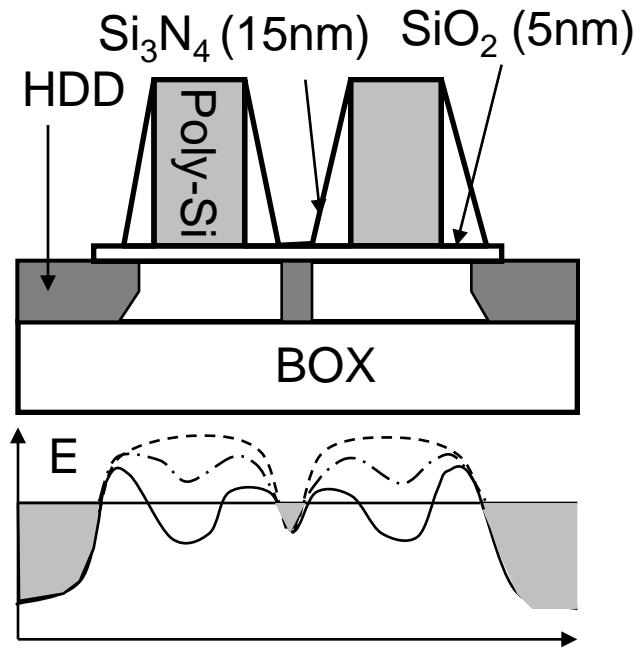
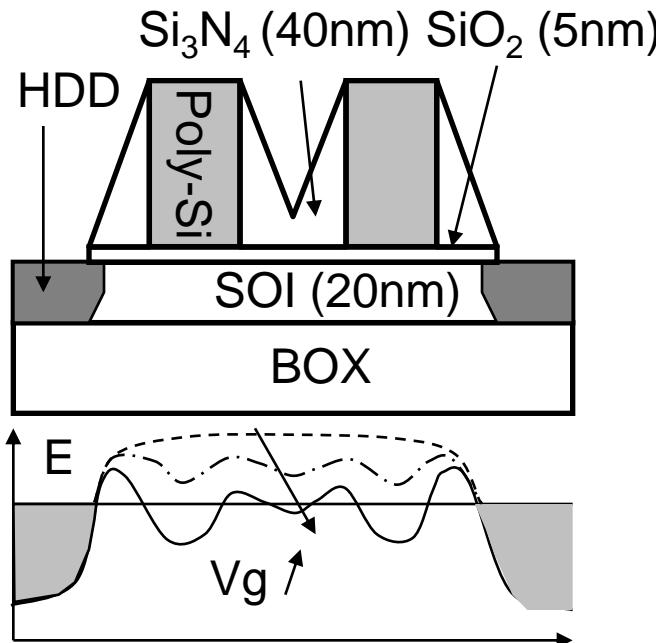
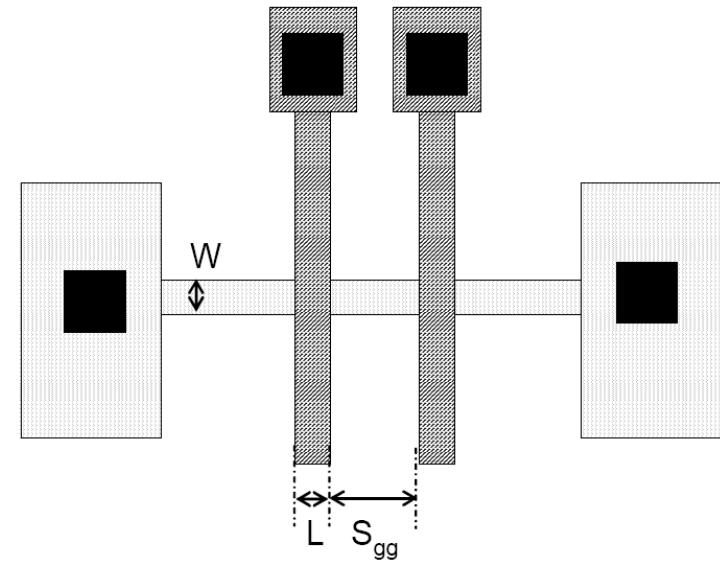
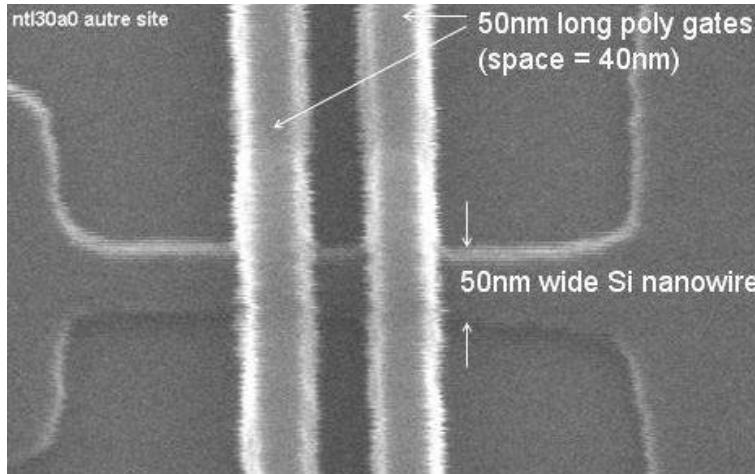


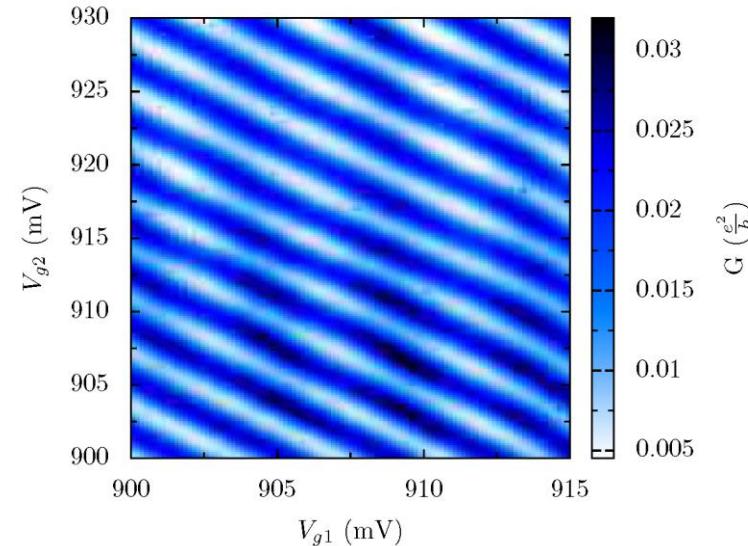
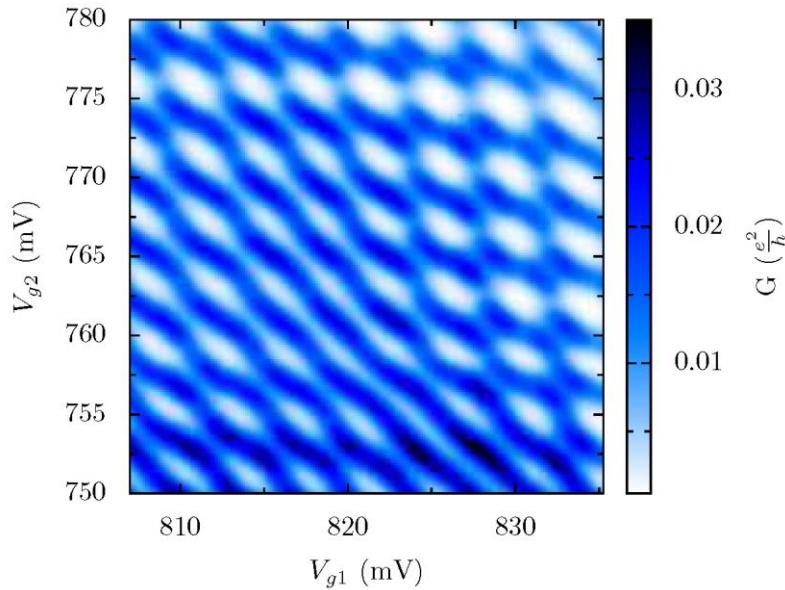
20nm isolated devices
40nm long lines 40nm spaced

for AFSiD: PITCH=70 nm
state-of-the-art for the **CEA/LETI-MINATEC CMOS foundry**
Benefits of a dedicated Silicon Fab line



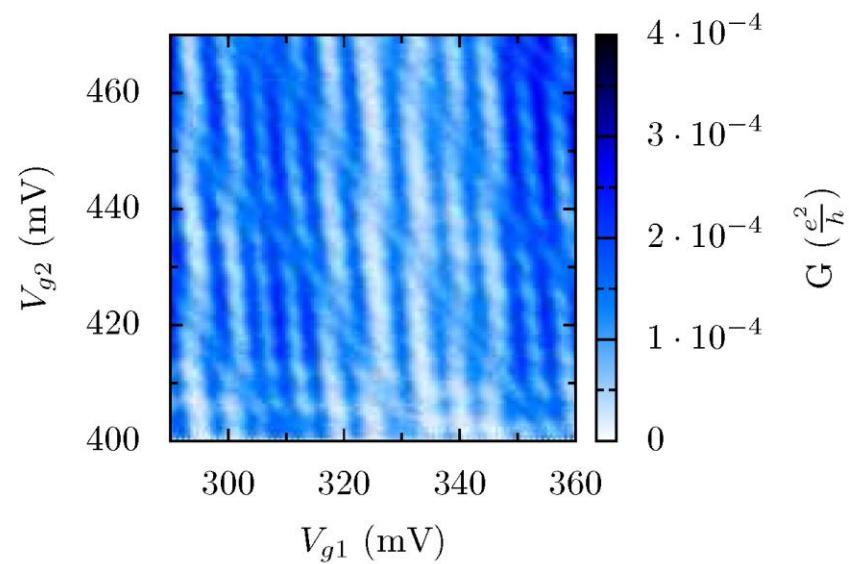
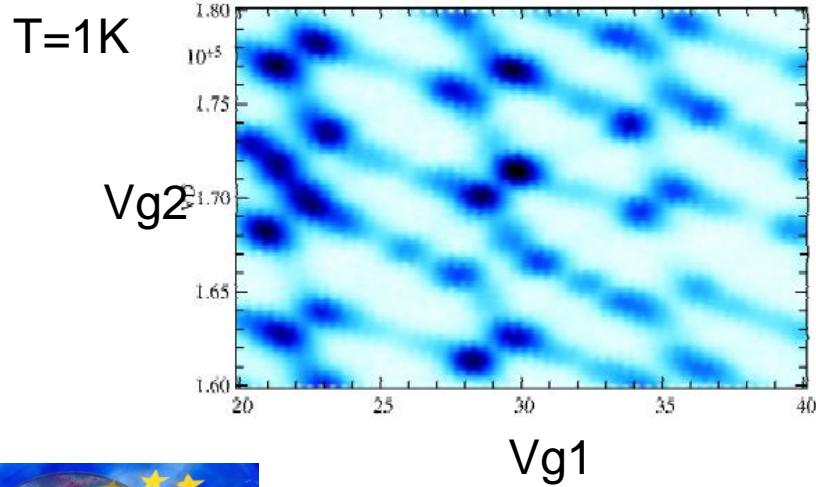
After gate etching, before spacer deposition



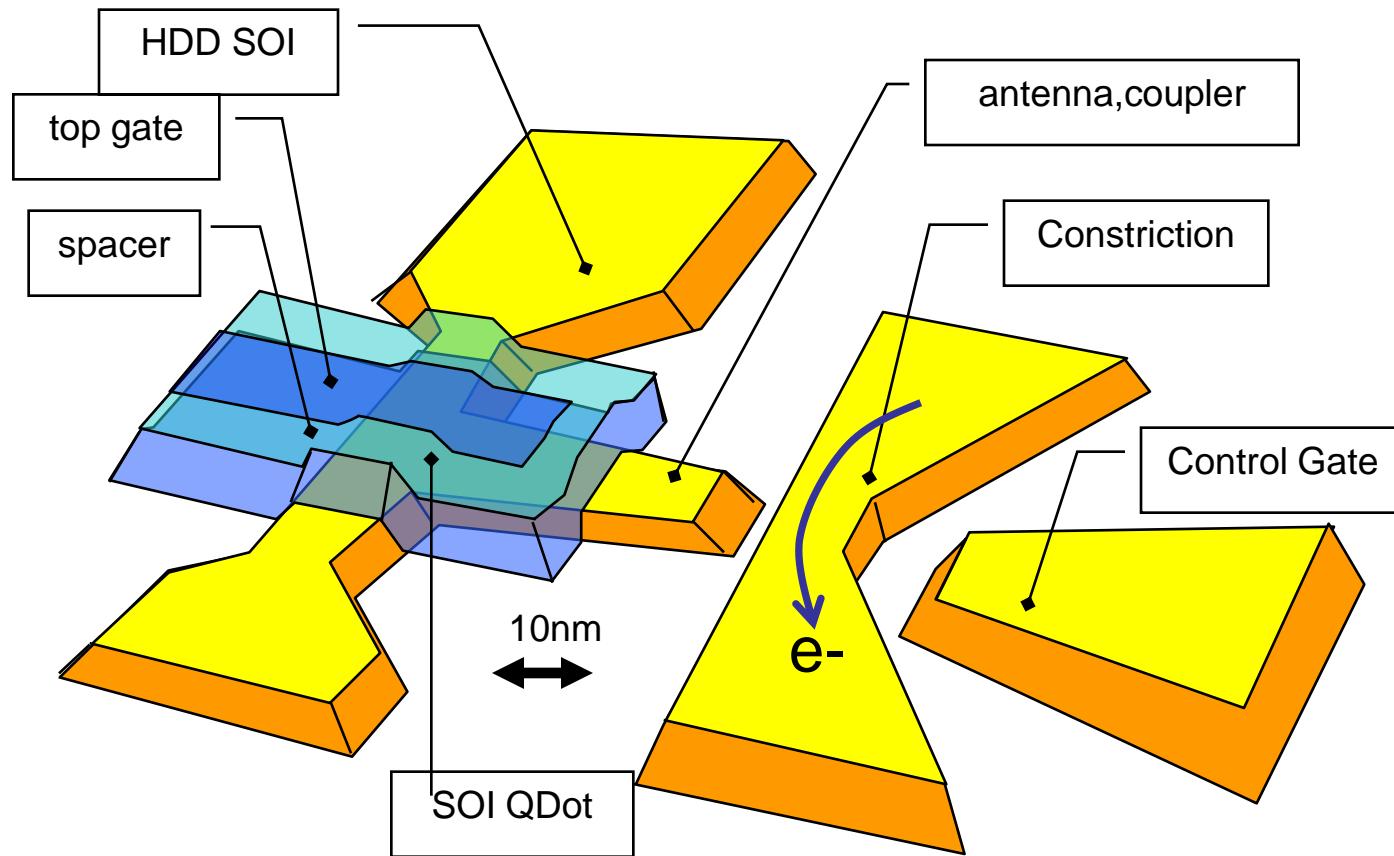


$T=4.2K$

VERY compact double (triple) MOS-SETs with tunable coupling



MOS-SET as an electrometer: need an antenna to couple external potential

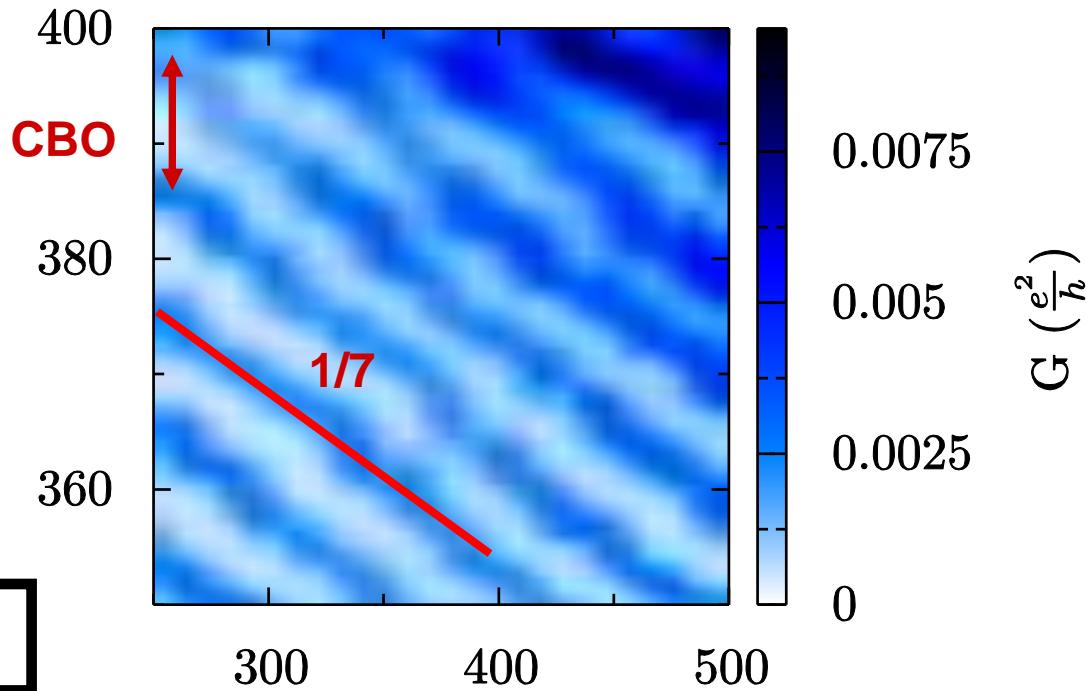
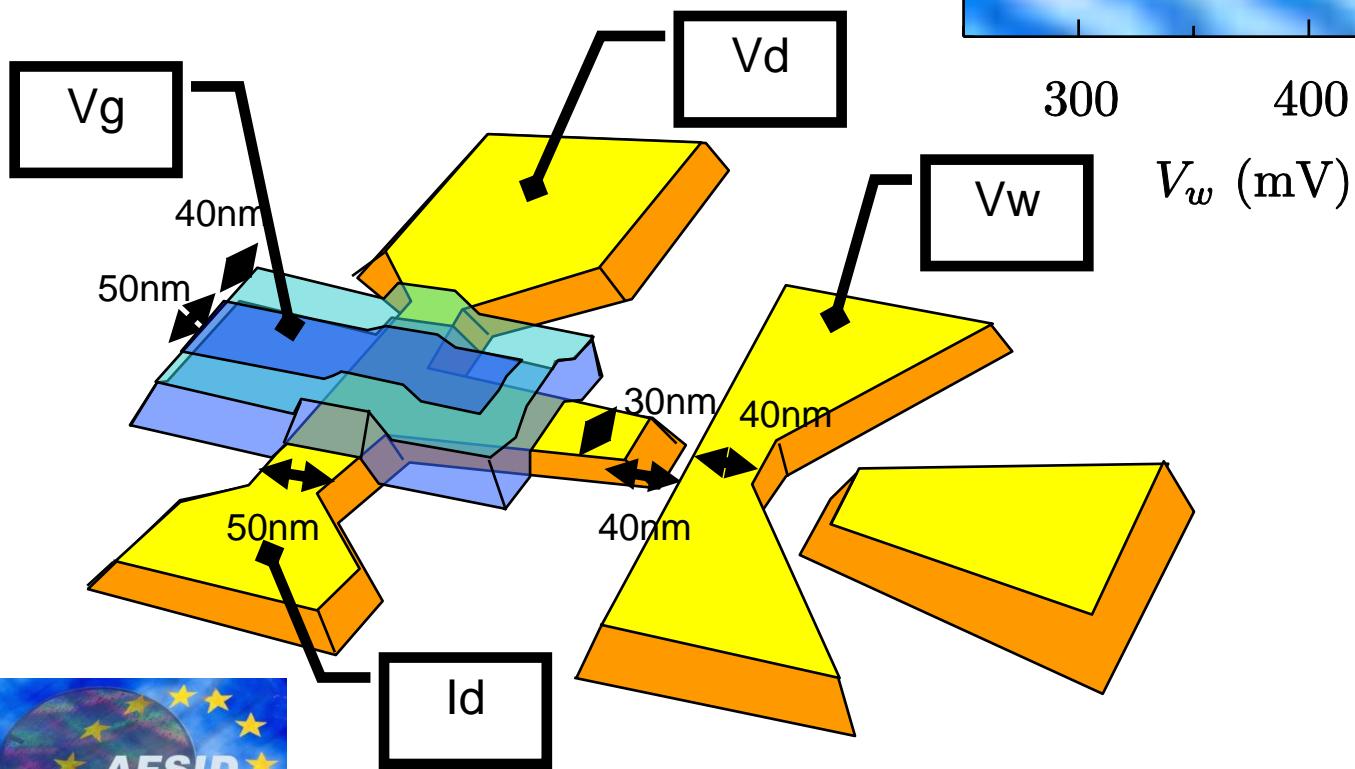


(CMOS) SET + QPC



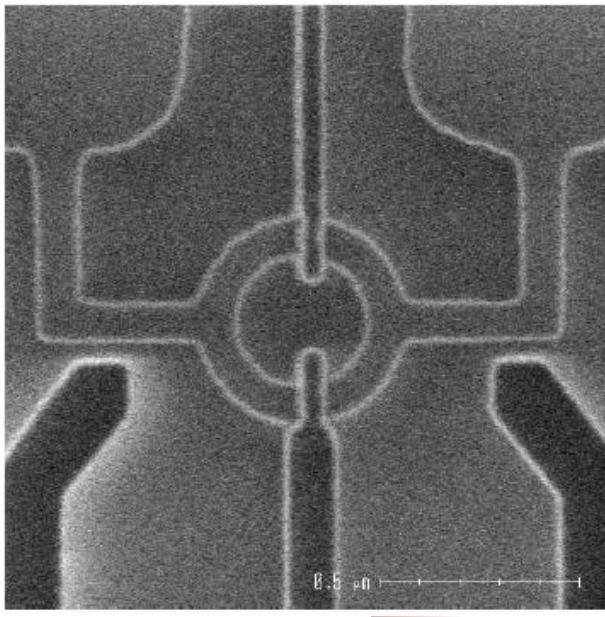
Strong coupling with external voltage

$T=4.2K$

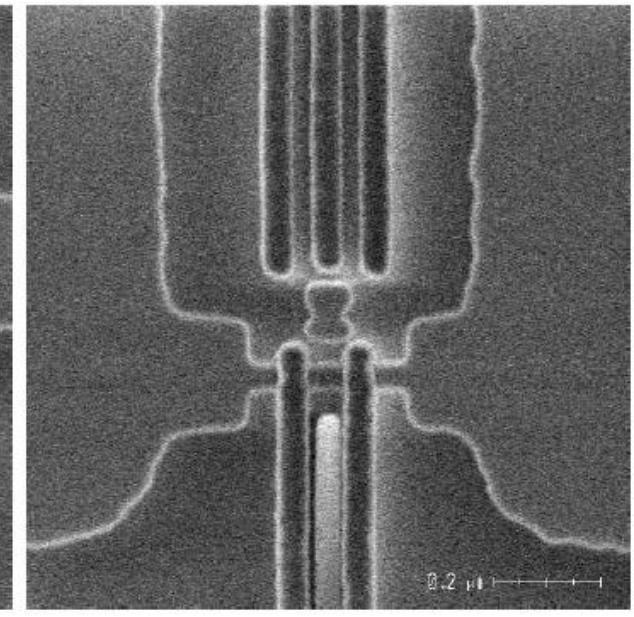
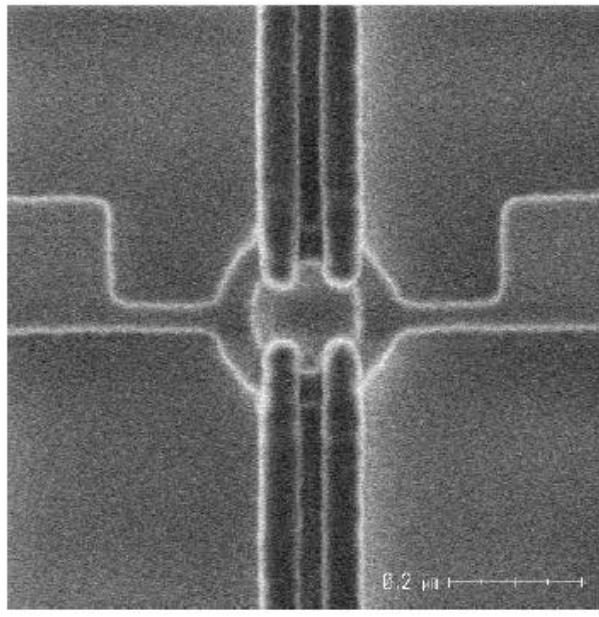


CMOS 200 mm wafers, ebeam fabrication of thousand's of quantum devices:

Aharonov-Bohm interferometers



Isolated double dot island



200 nm

Presentation by D. Williams



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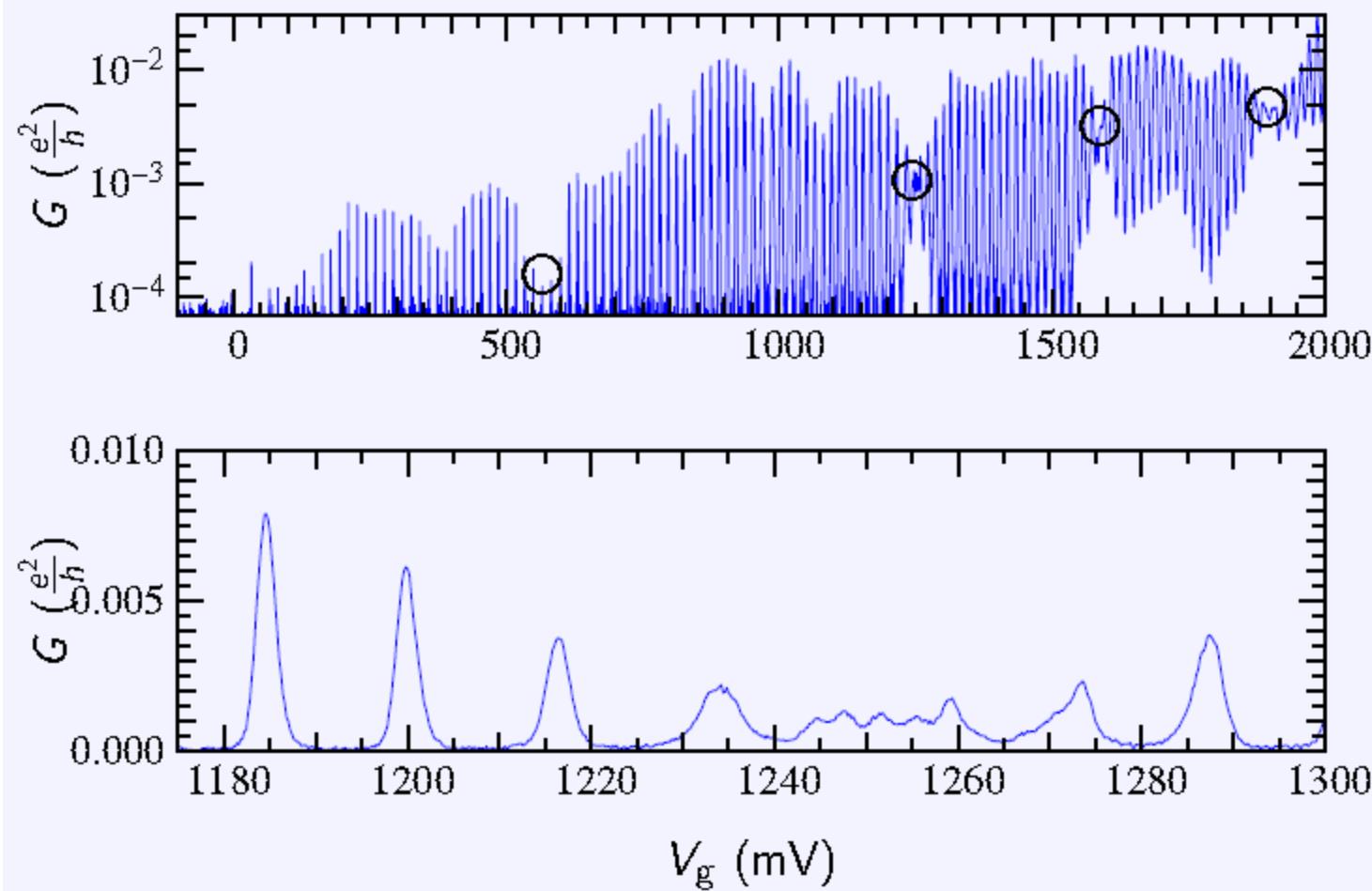
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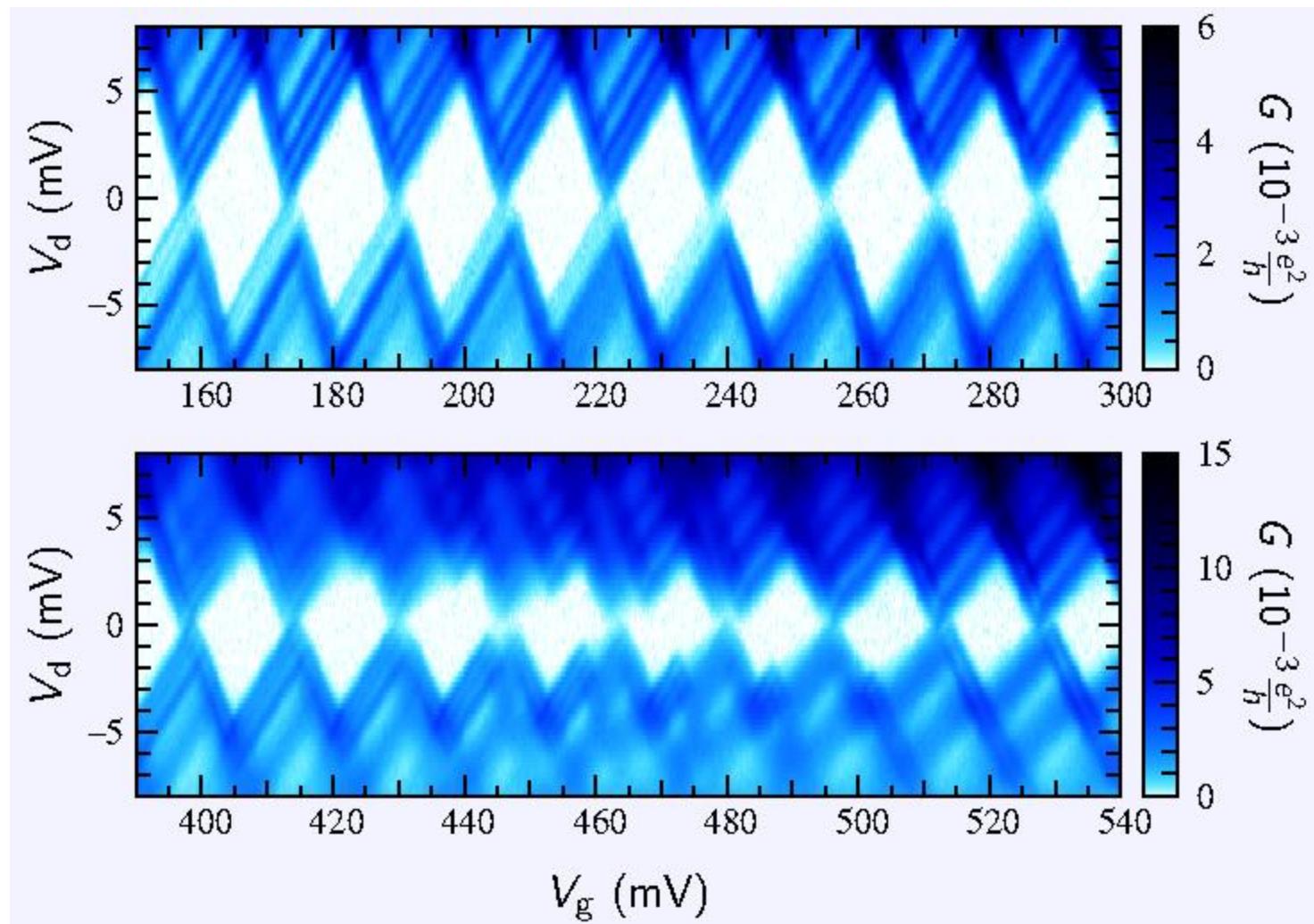
Single donor ionization detected with a MOS-SET

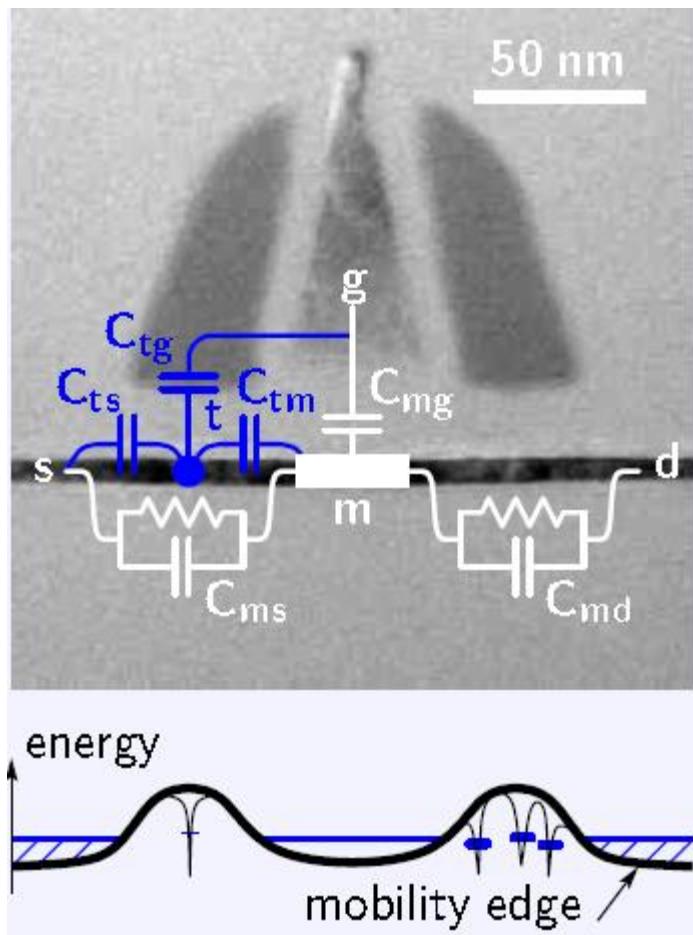
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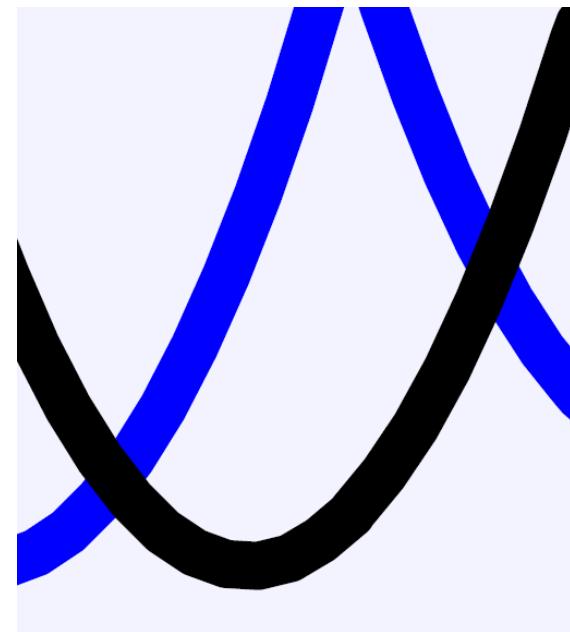
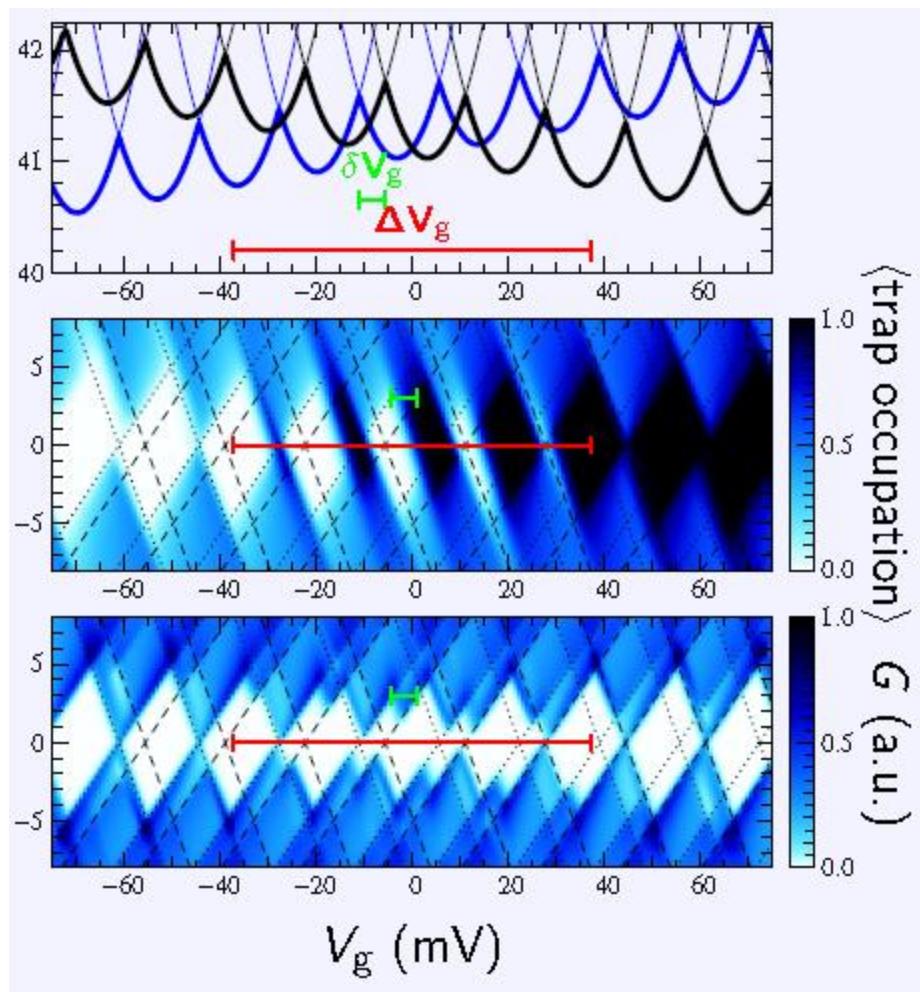
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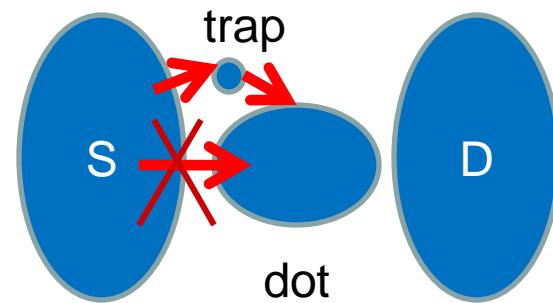






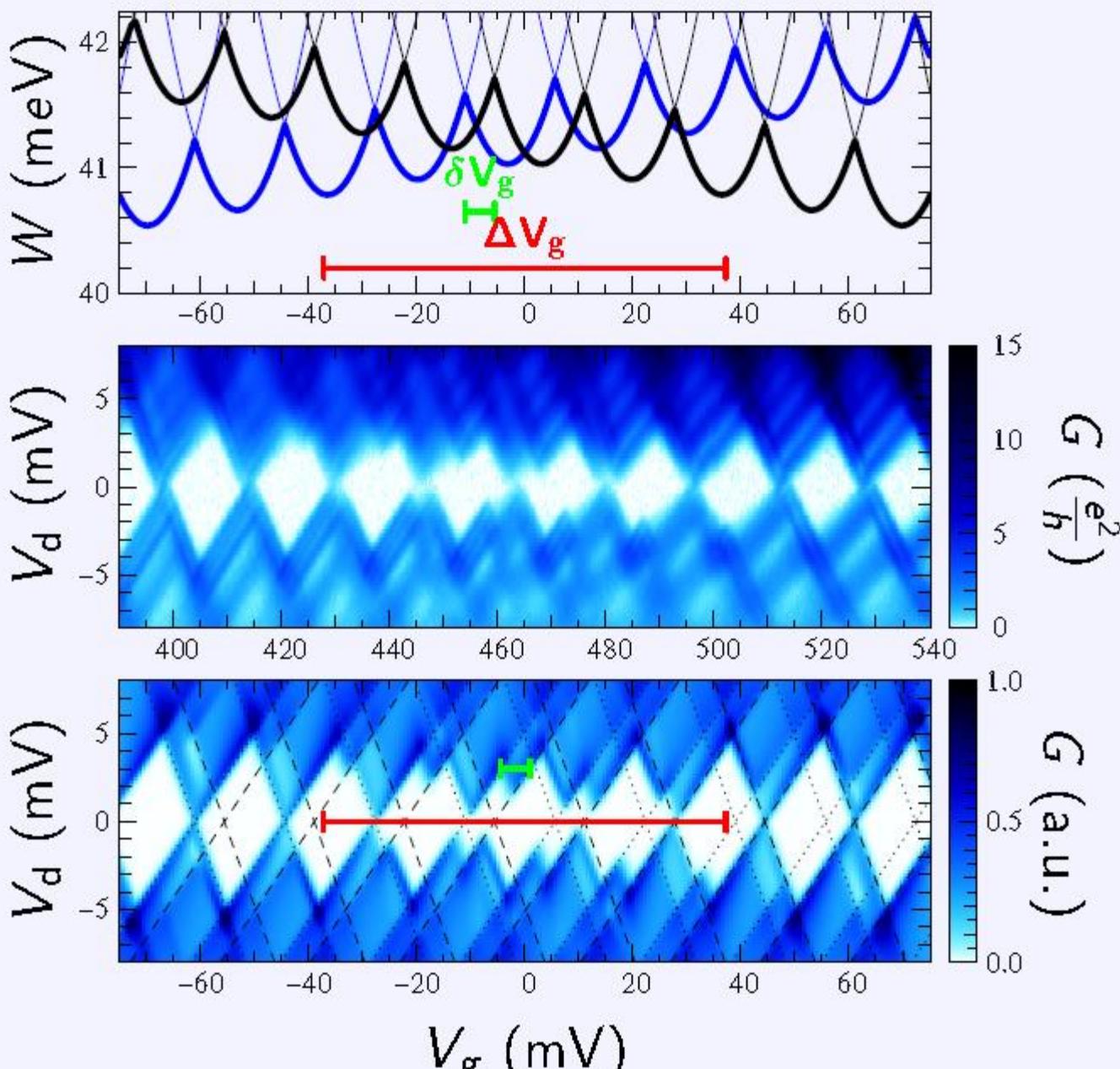


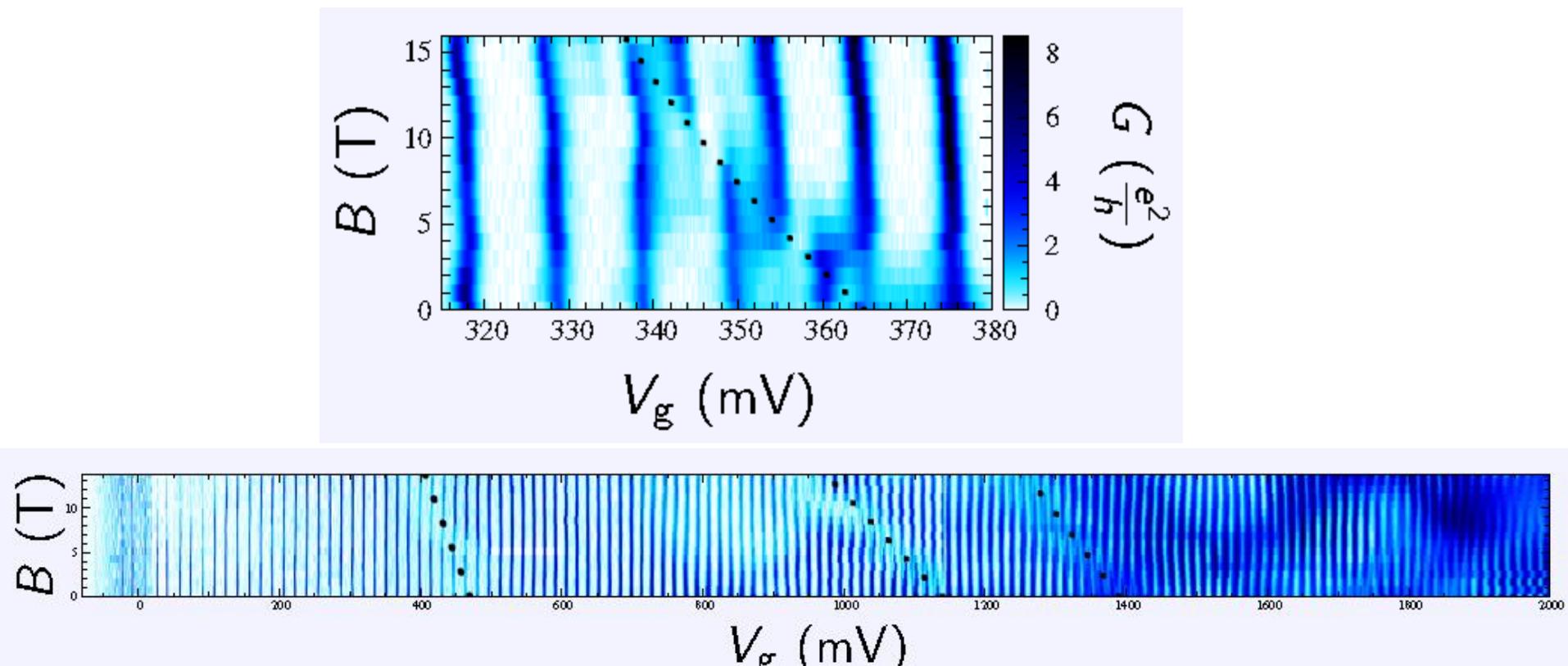
$(N,0) \rightarrow (N,1) \rightarrow (N+1,0)$



EXP

SIMUL



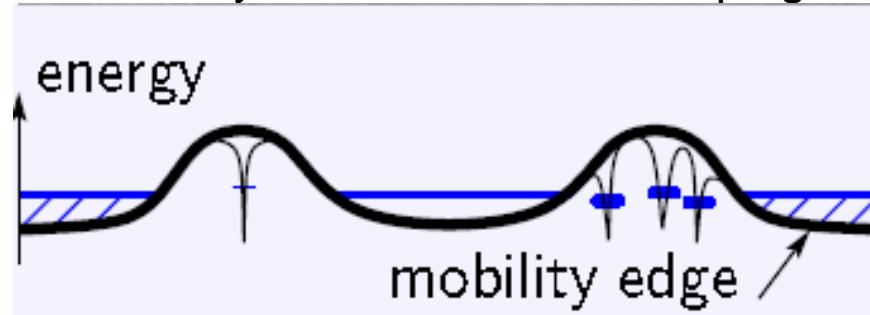


Spin $\frac{1}{2}$ detected through the Zeeman effect ($g=2$)

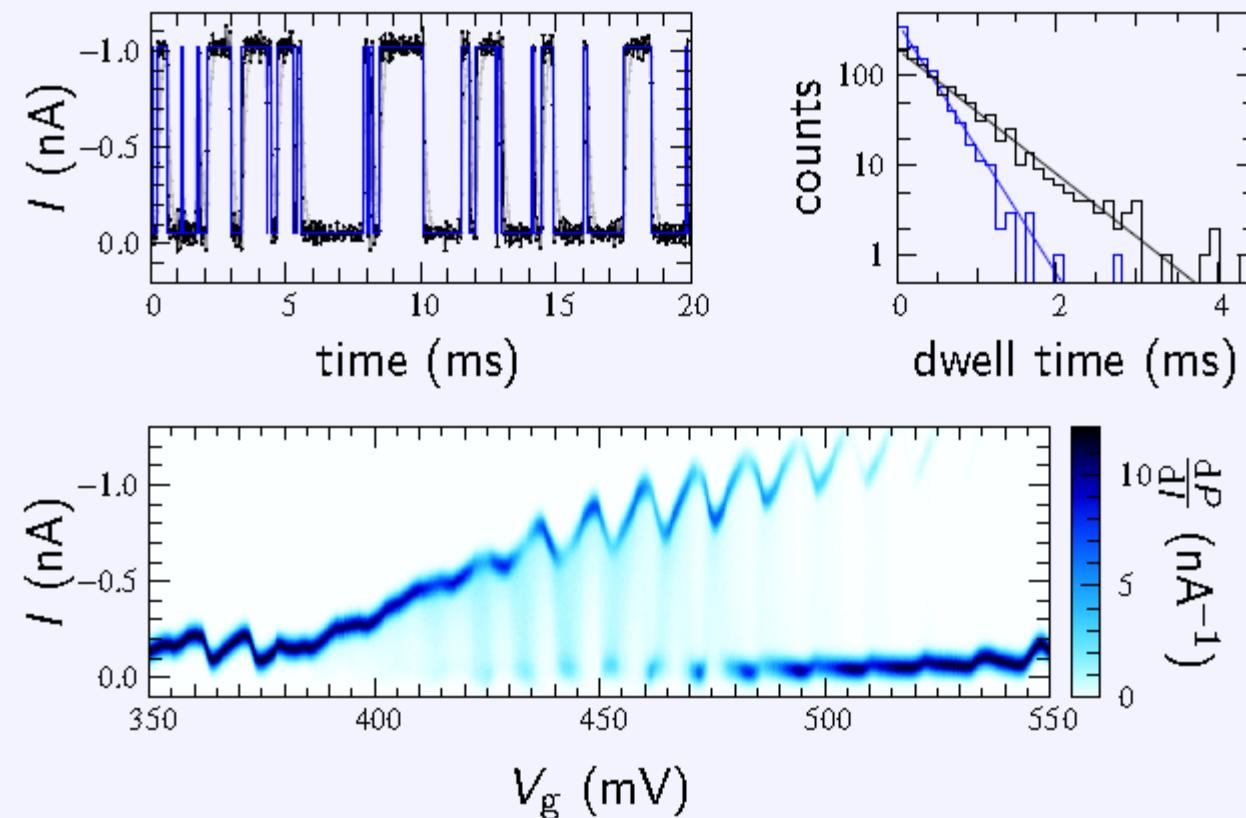


Traps are identified as single As donors implanted in the SiNW below the nitride spacers:

- Small lever arm parameter for the trap (small gate coupling) and quantitative analysis of the capacitance matrices
- Very large distribution of tunnel coupling to the reservoirs (slow traps → fast traps from few kHz to few GHz)
- Comparison with flash memory devices (with Si NC in gate stack)
- Preliminary results for various doping concentrations



Real time ionization state determination for a « slow » trap (single shot charge sensing)

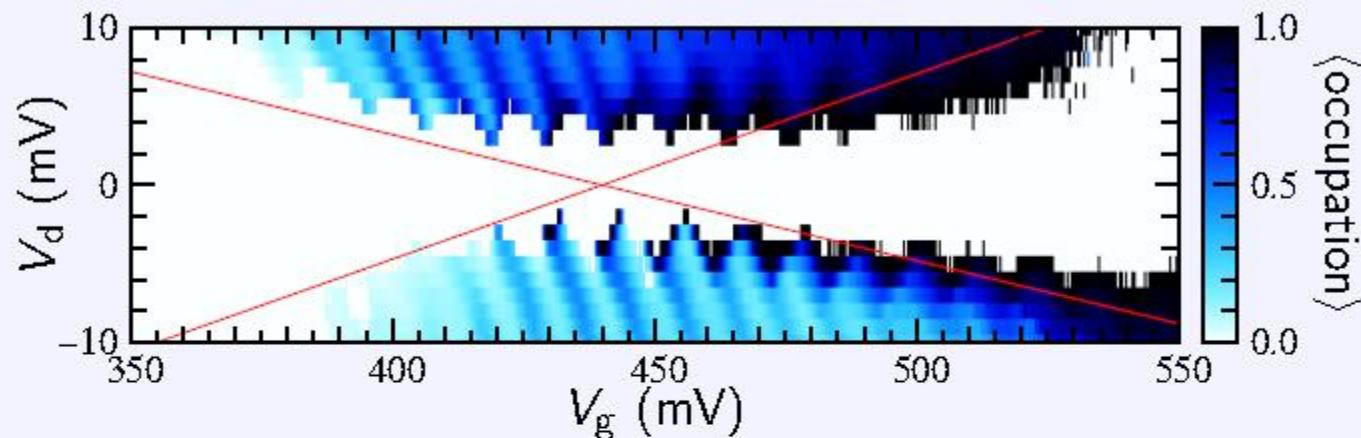


- All data at $V_d = -6$ mV, upper panels at $V_g = 500$ mV.
- Only possible if trap slower than measurement ($\approx 30 \mu\text{s}$).

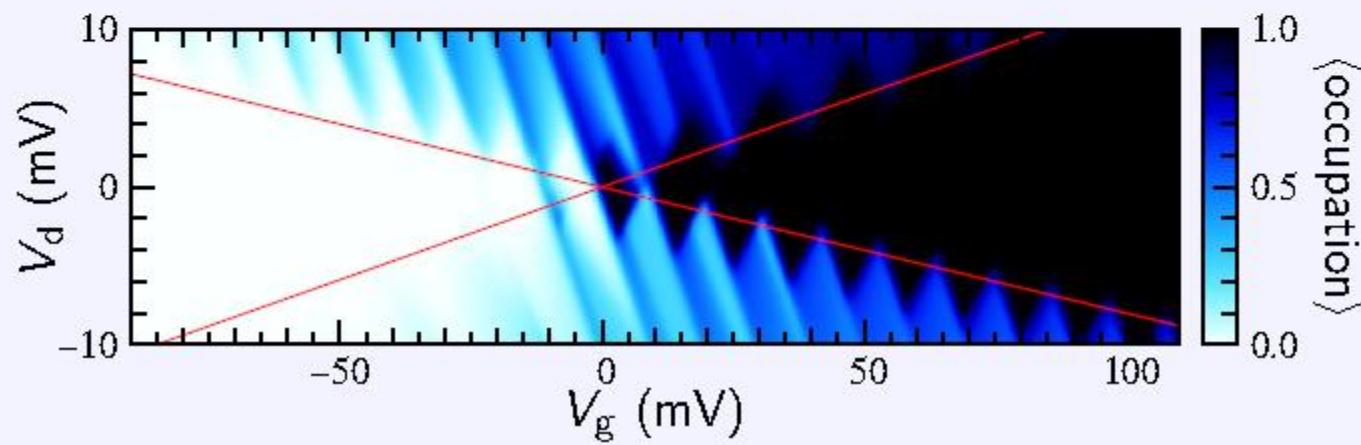
Fujisawa *et al.* APL 84 2343 (2004) Bylander *et al.* Nature 434 361 (2005) Gustavsson *et al.* PRL 96 076605 (2006)



measured mean trap occupation



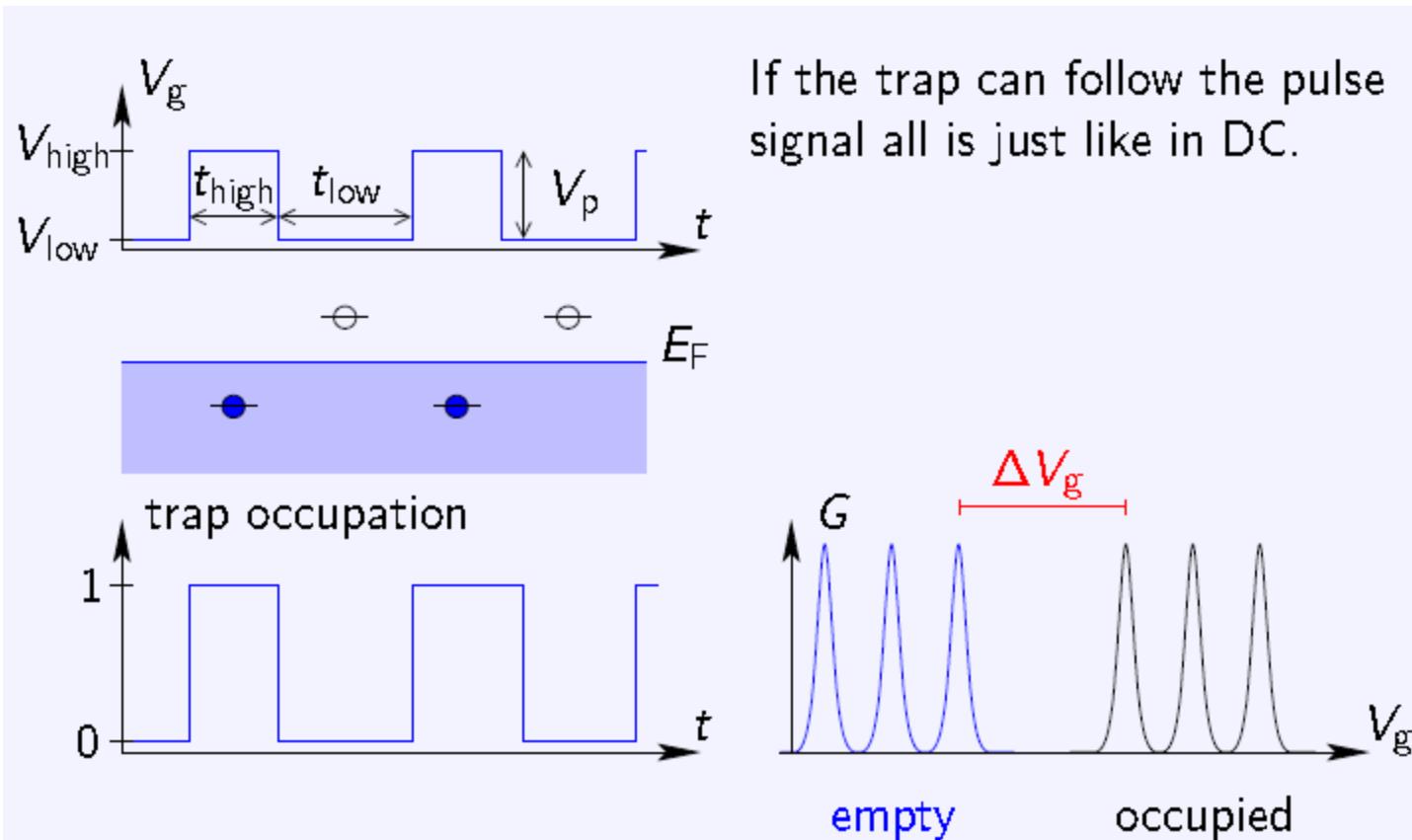
simulated mean trap occupation



Oscillation of mean trap occupation comes from the BACK-ACTION of the SET detector



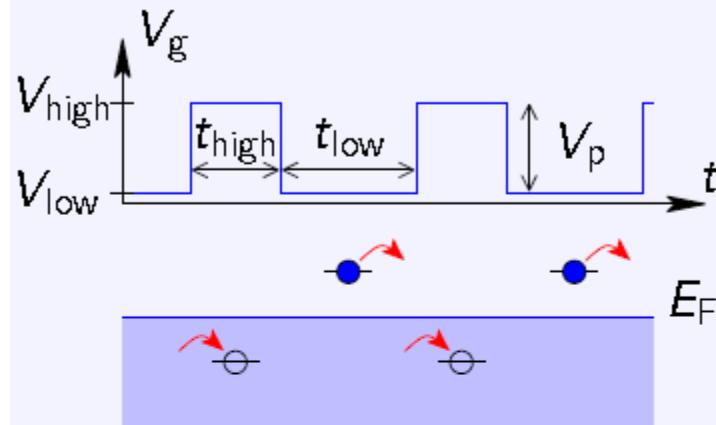
Pulsed gate voltage experiments for « fast » traps



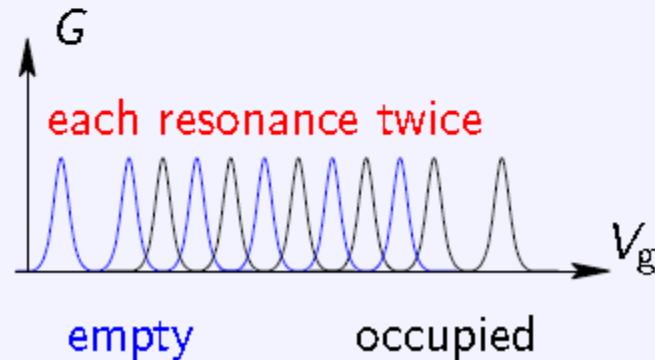
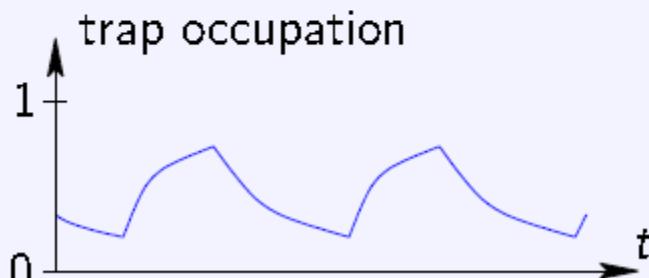
M. Hofheinz et al., unpublished

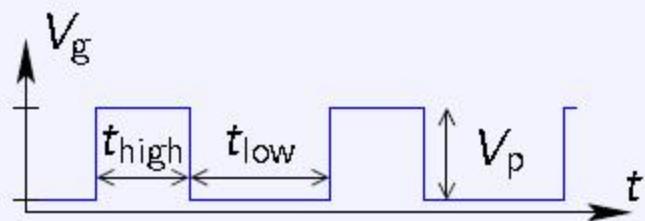
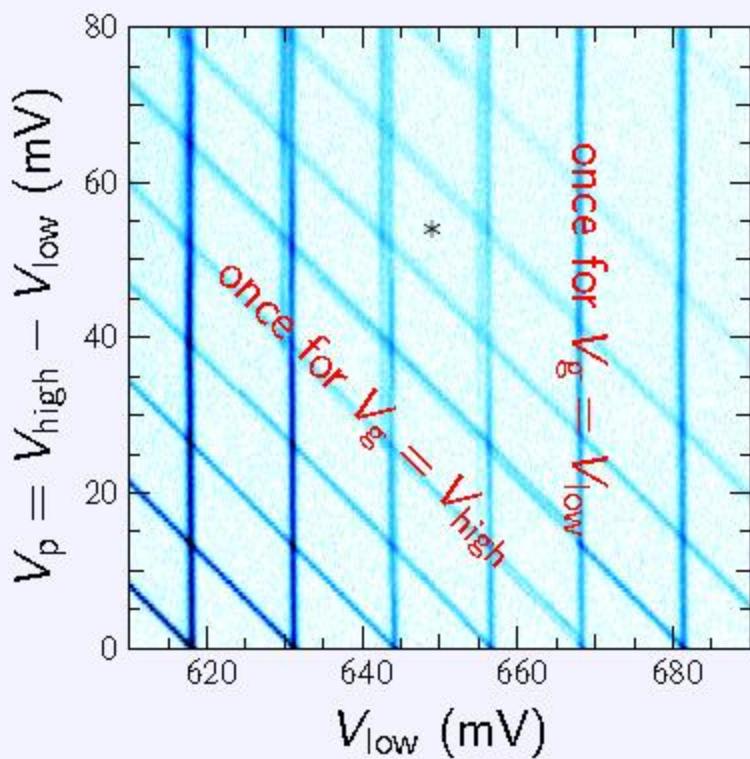


Out of equilibrium effects



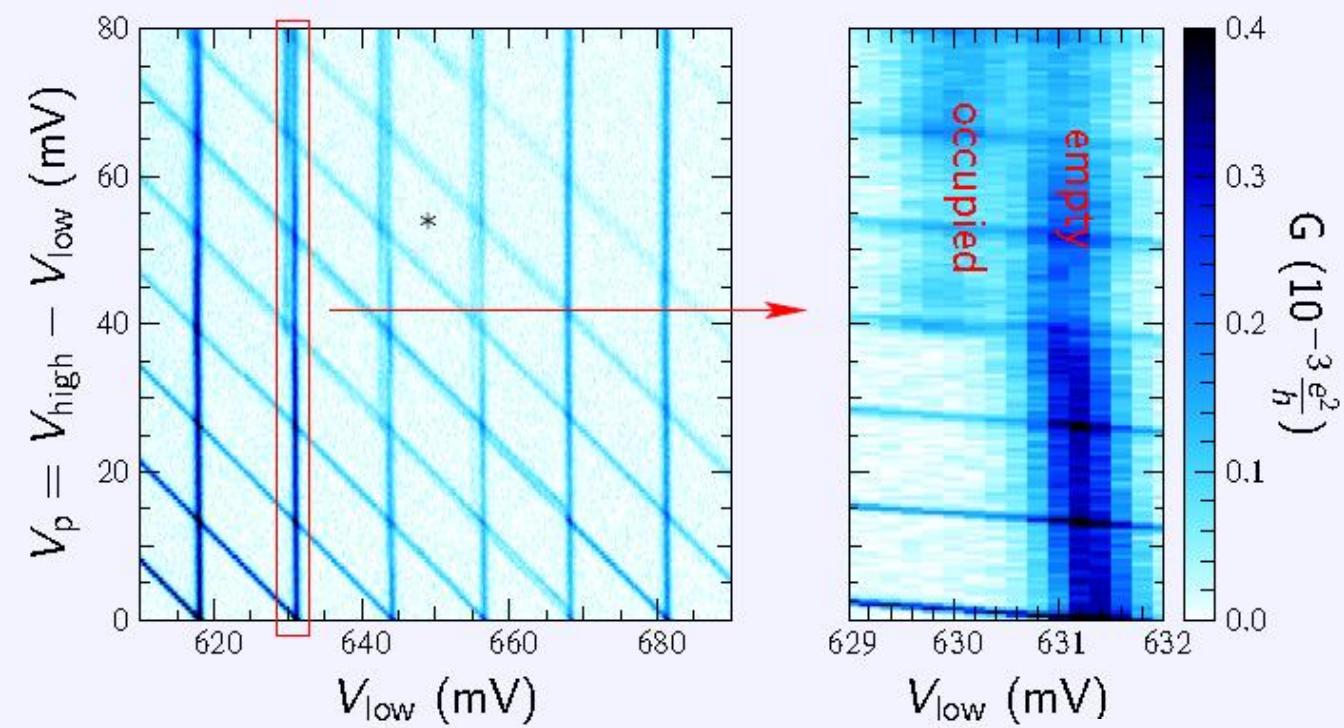
If the trap cannot follow the pulse signal, non-equilibrium charge states are observed.
→ resonances observed for empty and occupied traps.





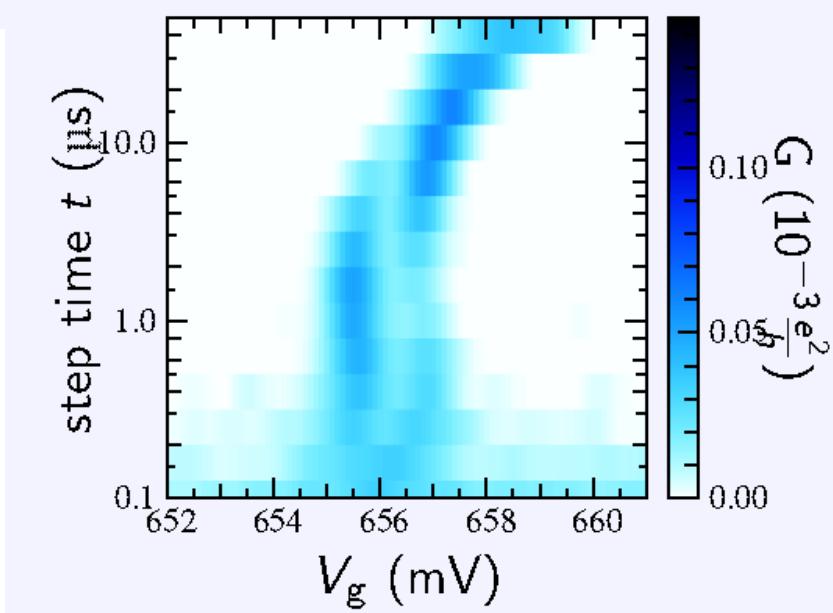
$$t_{\text{high}} = t_{\text{low}} = 1 \mu\text{s}$$

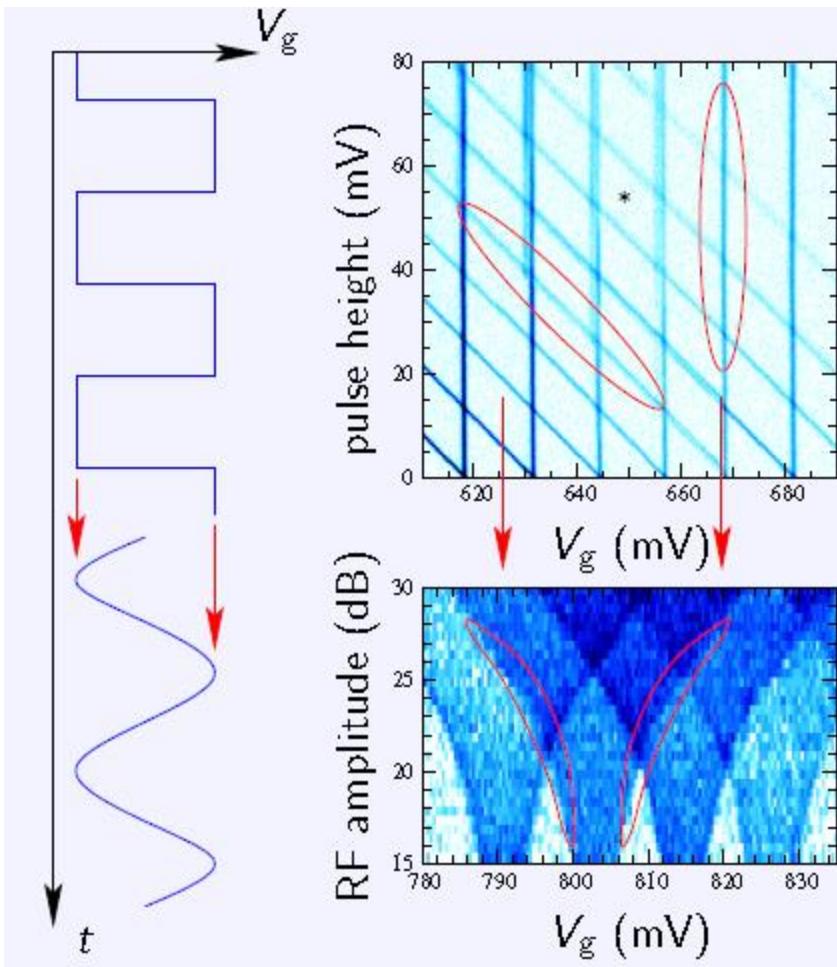
*PhD thesis, M. Hofheinz,
université J. Fourier 2006,
Grenoble, unpublished
(<http://tel.archives-ouvertes.fr/tel-00131052/en/>)*



For different pulse frequencies:

*PhD thesis, M. Hofheinz,
université J. Fourier 2006,
Grenoble, unpublished
(<http://tel.archives-ouvertes.fr/tel-00131052/en/>)*



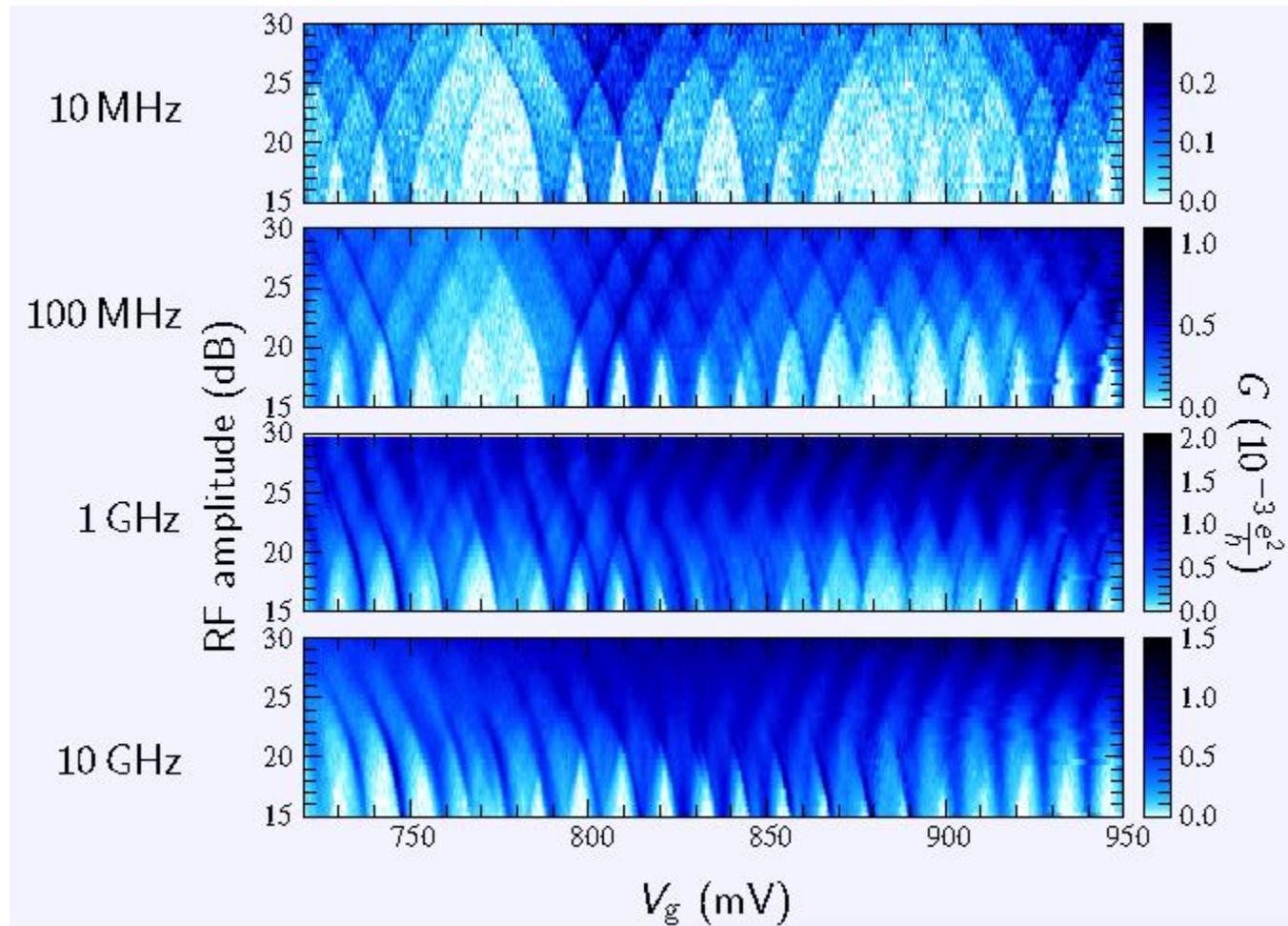


Sinusoidal instead
of step-like excitation for
frequencies above few MHz

*PhD thesis, M. Hofheinz,
université J. Fourier 2006,
Grenoble, unpublished
(<http://tel.archives-ouvertes.fr/tel-00131052/en/>)*



Out-of-equilibrium trap occupation re-establishes current through the dot



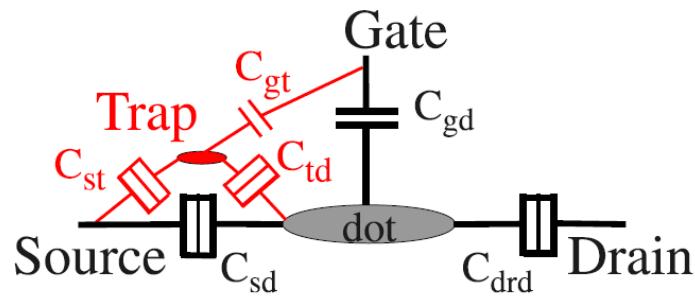
*PhD thesis, M. Hofheinz, université J. Fourier 2006,
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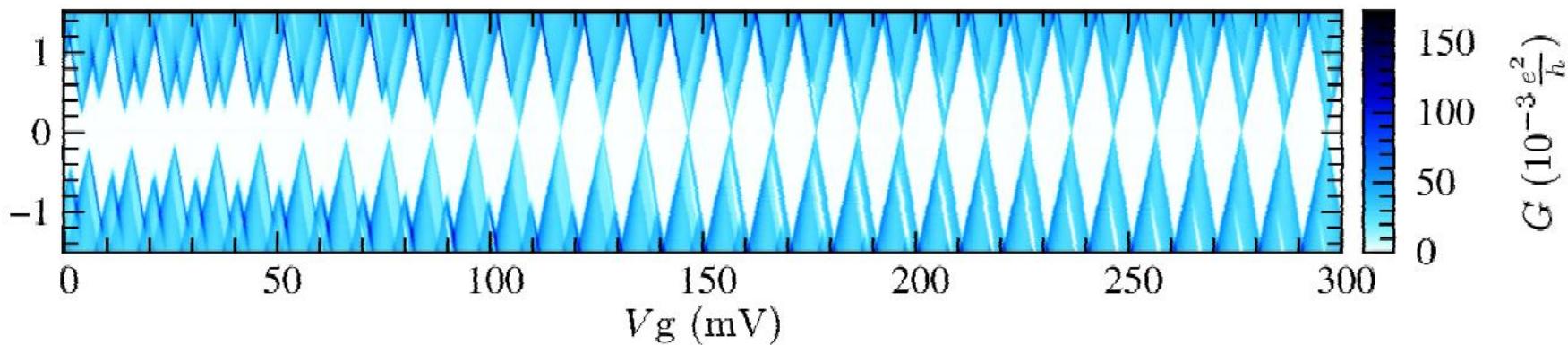
Impact of the model beyond the MOS-SET for quantum dot spectroscopy

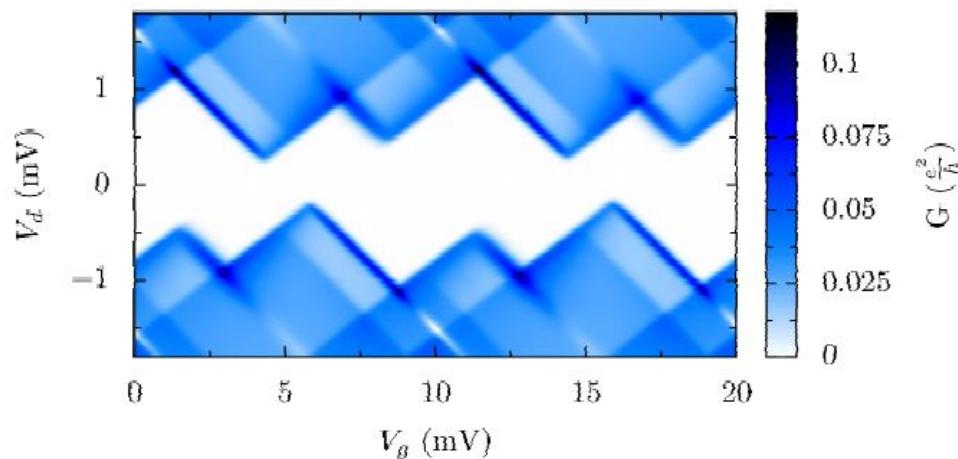
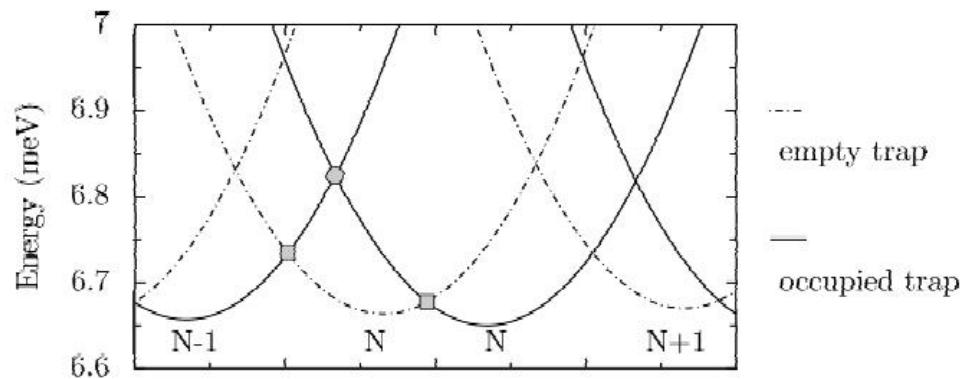
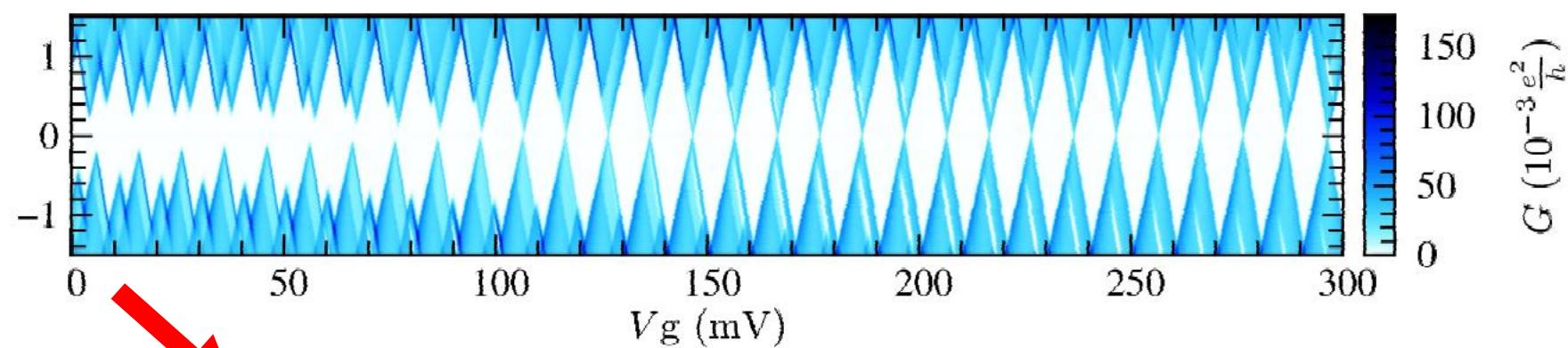
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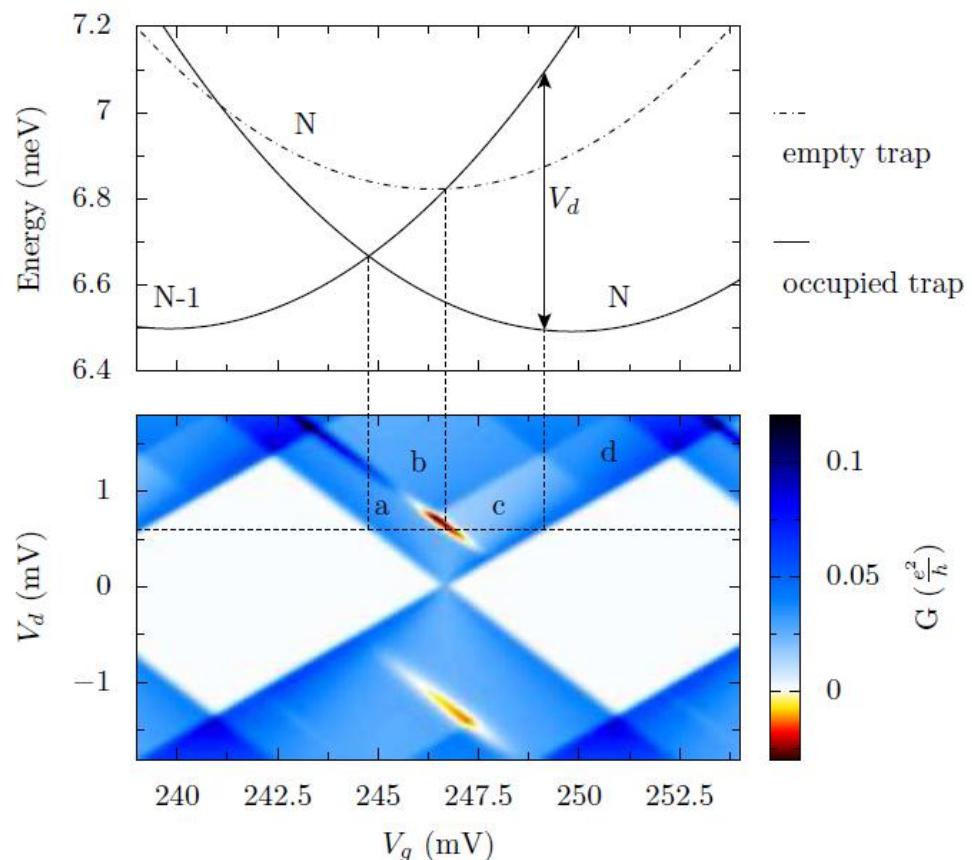
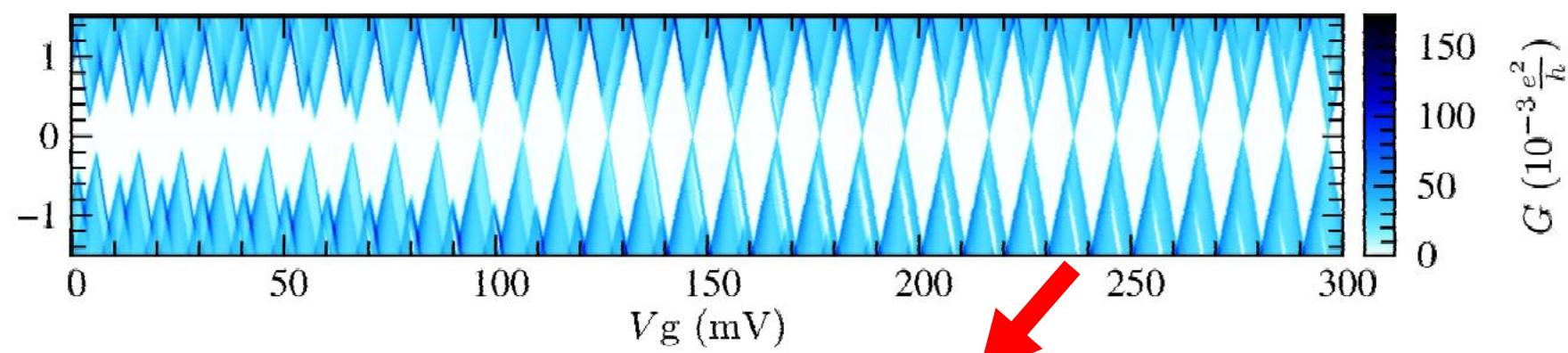
The model gives distorted diamonds AND differential conductance lines in undistorted diamonds:



Orthodox theory of CB for the dot

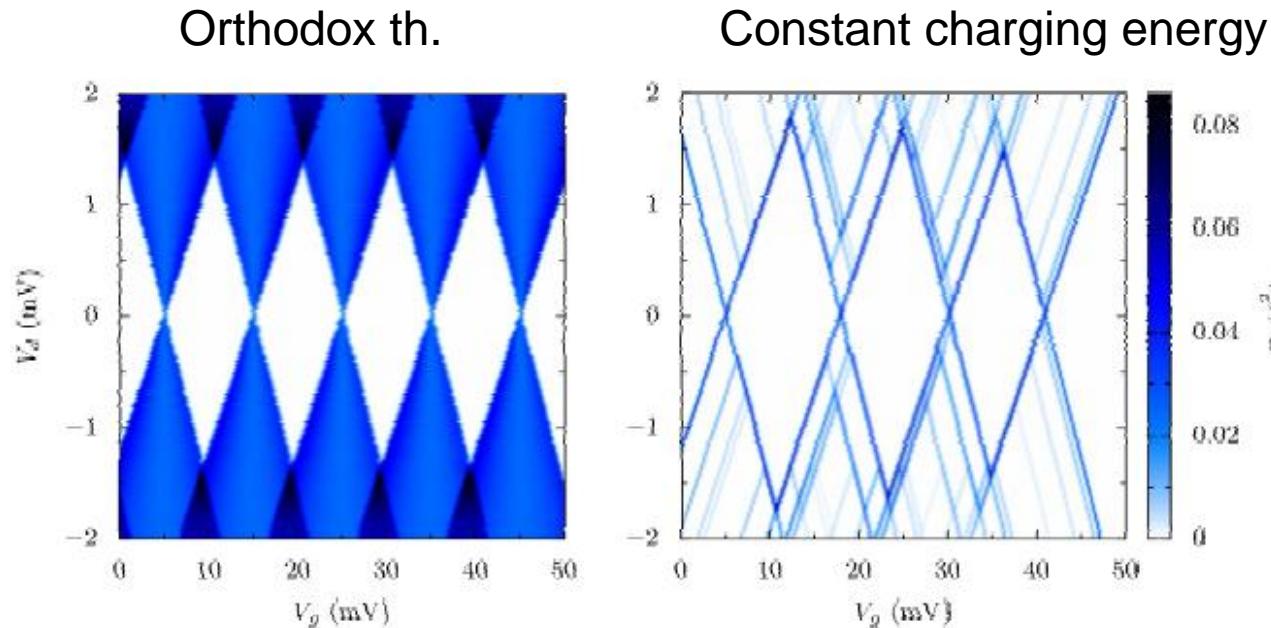




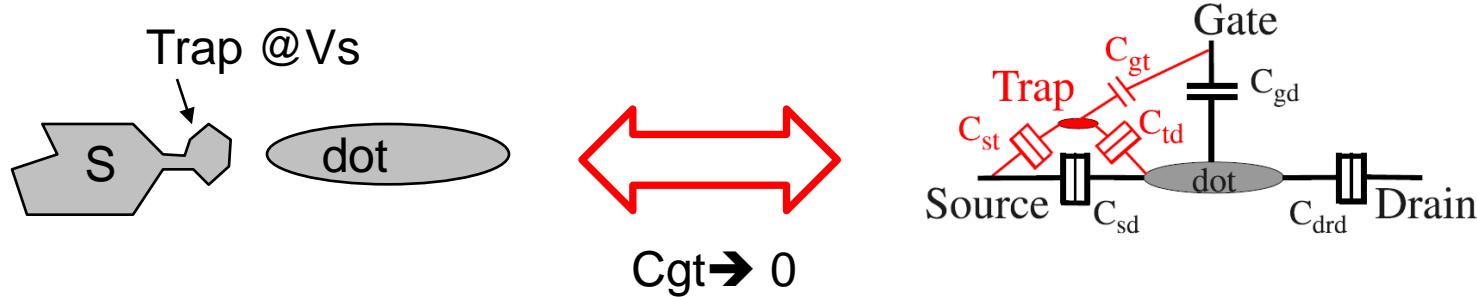


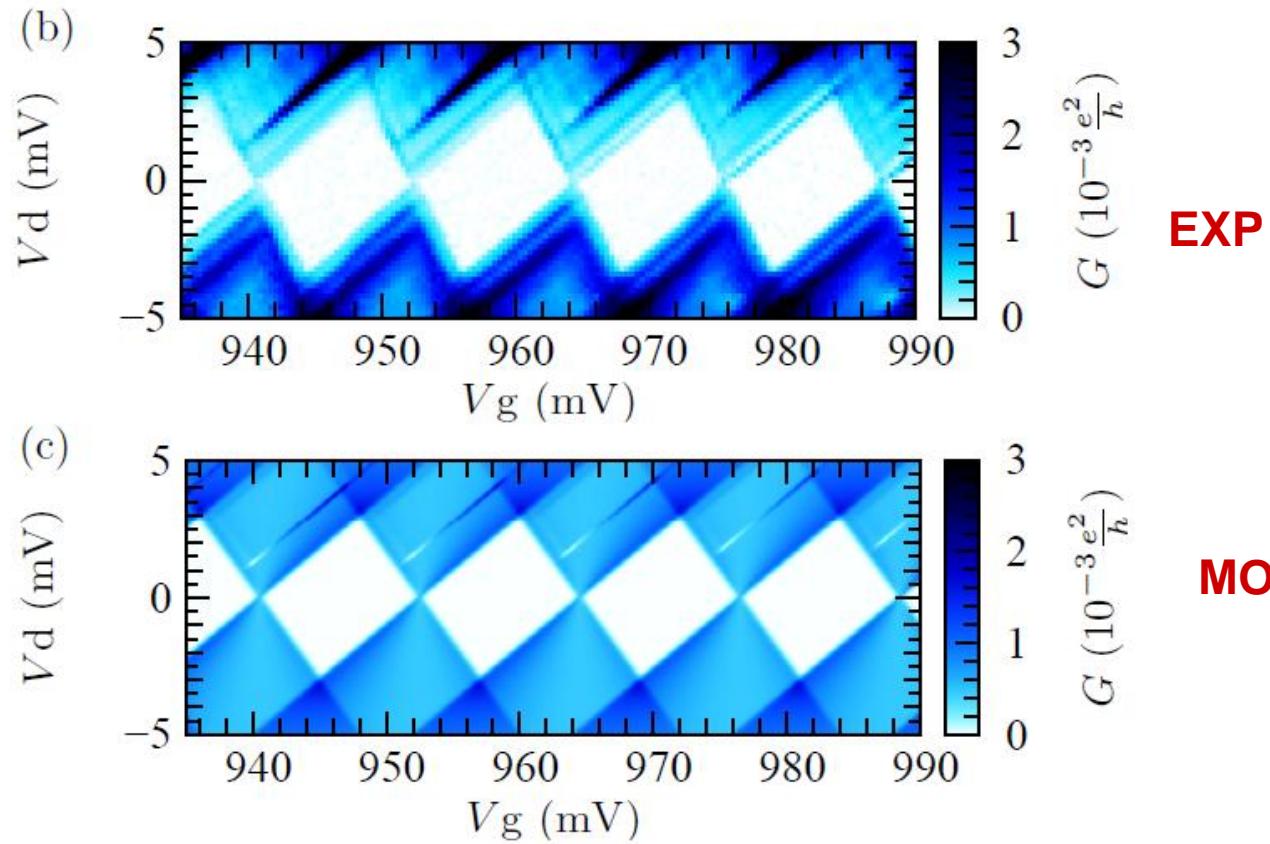
Simple electrostatic model in contrast to quantum based explanations:

1) quantum excitation spectrum of Quantum Dots



2) DoS in the reservoirs





Summary:

- ➔ MOS-SET of size 30nm realized, size 10nm reachable for single MOS-SETs
- ➔ Compact coupled MOS-SET with 70 nm pitch and MOS-SET with antenna realized
- ➔ MOS-SET has been used to detect (dynamically) individual As donors (location, spin, tunnel couplings)
- ➔ General problem of donors located near the MOS-SET (implanted or diffused from S-D): it appears because S-D are very close to the dot in our very compact design. It could be partially solved by using silicided S-D (NiSi), undoped source-drain (2DEG S-D), isolated dots...

